

LOW-IONIZATION LINE EMISSION FROM STARBURST GALAXIES: A NEW PROBE OF GALACTIC-SCALE OUTFLOWS

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ABSTRACT

We study the kinematically narrow, low-ionization line emission from a bright, starburst galaxy at $z = 0.69$ using slit spectroscopy obtained with Keck/LRIS. The spectrum reveals strong absorption in Mg II and Fe II resonance transitions with Doppler shifts of -200 to -300 km s⁻¹, indicating a cool gas outflow. Emission in Mg II near and redward of systemic velocity, in concert with the observed absorption, yields a P Cygni-like line profile similar to those observed in the Ly α transition in Lyman Break Galaxies. Further, the Mg II emission is spatially resolved, and extends significantly beyond the emission from stars and H II regions within the galaxy. Assuming the emission has a simple, symmetric surface brightness profile, we find that the gas extends to distances $\gtrsim 7$ kpc. We also detect several narrow Fe II* fine-structure lines in emission near the systemic velocity, arising from energy levels which are radiatively excited directly from the ground state. We suggest that the Mg II and Fe II* emission is generated by photon scattering in the observed outflow, and emphasize that this emission is a generic prediction of outflows. These observations provide the first direct constraints on the minimum spatial extent and morphology of the wind from a distant galaxy. Estimates of these parameters are crucial for understanding the impact of outflows in driving galaxy evolution.

Subject headings: galaxies: ISM — galaxies: halos — galaxies: starburst

1. INTRODUCTION

Galactic-scale outflows may be a primary driver of galaxy evolution through the removal of cool gas from star-forming regions to a galaxy's halo or beyond. Measurements of outflow properties in distant galaxies, such as the mass and energy outflow rates, are central to understanding their role in feedback and quenching processes. However, accurate determinations of these outflow rates require knowledge of the spatial extent of the wind, a parameter that is difficult to constrain observationally.

While winds are detected in optical line and X-ray emission around local starburst galaxies to distances of several kiloparsecs (e.g., Heckman et al. 1990; Martin 1999), because this emission is faint, outflows in distant galaxies have traditionally been detected only in absorption against the stellar continuum. This technique probes cool gas ($T \lesssim 10^4$ K) traced by transitions such as Na I D (e.g., Rupke et al. 2005) and Mg II (e.g., Weiner et al. 2009; Rubin et al. 2010b), and constrains the outflow velocity, covering fraction, and column density. Recently, Ménard et al. (2009) also showed that Mg II absorption tracks the overall star formation history of the Universe. However, these absorption-line studies provide only weak constraints on the radial extent, spatially-resolved geometry, and volume density of the outflow. In turn, estimates of the rates of mass and energy loss are uncertain by at least two orders of magnitude. Improved constraints are critical for understanding the role played by

outflows in polluting a galaxy's halo and the surrounding intergalactic medium.

A novel technique for studying outflows in the distant universe is analysis of emission from the outflowing gas. This emission may arise from resonance-line scattering off of the flow or fluorescent radiation powered by luminous star clusters. In the former case, the emission, with the corresponding absorption, may exhibit a P Cygni-like line profile. The high optical depth of the Ly α transition results in P Cygni profiles observed in the spectra of Lyman Break Galaxies (LBGs; e.g., Pettini et al. 2001, 2002). Although it has much lower optical depth than Ly α , Mg II $\lambda\lambda 2796, 2803$ photons can also be resonantly trapped and will produce strong emission where the gas is optically thick (i.e., at hydrogen column densities of $N_H \sim 10^{19}$ cm⁻²). In contrast, optically thick Fe II resonance absorption is not trapped, but pumps UV Fe II* emission lines at $\sim 2000 - 3000$ Å. In principle, Mg II and Fe II* emission can be particularly useful for tracing winds at $z > 0.3$, where it is detected into the optical; moreover, Mg II emission has already been detected in $z \sim 1$ star-forming galaxies (Weiner et al. 2009; Rubin et al. 2010b). Measurement of the spatial extent of this line emission provides a firm lower limit on the radial extent of the outflow and constrains the wind morphology.

In this paper, we examine the line emission from a bright starburst at $z = 0.694$ known to exhibit a P Cygni profile in Mg II and Fe II* emission (Rubin et al. 2010a). We report in detail on the observed characteristics of the emission and suggest possible production mechanisms. We adopt a Λ CDM cosmology with $H_0 = 70$ km s⁻¹ Mpc⁻¹, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$.

2. OBSERVATIONS

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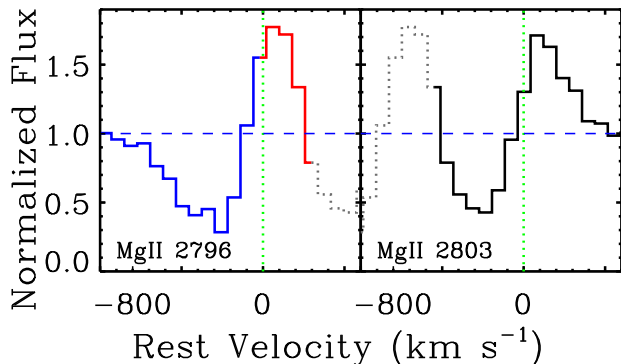


FIG. 1.— The Mg II line profile in the galaxy spectrum. Dotted portions of the spectrum are associated with the transition in the opposite panel. The systemic velocity is marked with vertical dotted lines, and the horizontal dashed line marks the continuum level. The profile exhibits blueshifted absorption extending to -800 km s^{-1} relative to the systemic velocity. Emission at and redward of systemic velocity is also evident. Together, these features exhibit a P Cygni profile, suggestive of a galactic outflow. We propose that the red and blue sections of the spectrum in the left-hand panel arise from different areas of the outflow, as indicated in Figure 4.

Details of our observations of the target galaxy (TKRS4389) and data reduction are given in Rubin et al. (2010a). We obtained spectroscopy of this galaxy using the Low Resolution Imaging Spectrometer (LRIS) on Keck 1 (Cohen et al. 1994). Our instrumental setup afforded a FWHM resolution ranging between $190 - 300 \text{ km s}^{-1}$ and wavelength coverage of $\sim 3200 - 7600 \text{ \AA}$. We used a $0.9''$ slitlet oriented NE (see Figure 1 of Rubin et al. 2010a) and collected six ~ 1800 sec exposures with FWHM $\sim 0.6''$ seeing. The data were reduced using the XIDL LowRedux⁴ data reduction pipeline.

3. ANALYSIS

As noted in Rubin et al. (2010a), this galaxy is exceptionally bright for its redshift, with a star formation rate of $\sim 80 M_{\odot} \text{ yr}^{-1}$. Stellar population modeling indicates that the spectrum is dominated by light from the intense star formation activity. The deepest parts of the Mg II and Fe II resonance *absorption* lines are blueshifted by $\sim 200 - 300 \text{ km s}^{-1}$, with high velocity tails extending to -800 km s^{-1} , indicating that these ions trace an outflow (see Figures 1 and 2). Here we analyze the characteristics of the observed *emission* from these ions.

3.1. Characteristics of Mg II Emission

The one-dimensional spectrum of this galaxy reveals strong Mg II emission near systemic velocity and extending to the red (Figure 1). We measure the kinematic extent v_{extent} of each emission line (Table 1) using standard techniques (Cooksey et al. 2008). Line fluxes are derived from integrating the continuum-subtracted spectrum over this velocity range. The continuum is measured from clean regions near each feature; its error is determined through Monte Carlo realizations. The flux-weighted velocity centroid of the lines is given as v_{cen} , and v_{peak} is the brightest pixel in each line (smoothed by 3 pixels; Table 1).

⁴ <http://www.ucolick.org/~xavier/LowRedux/>

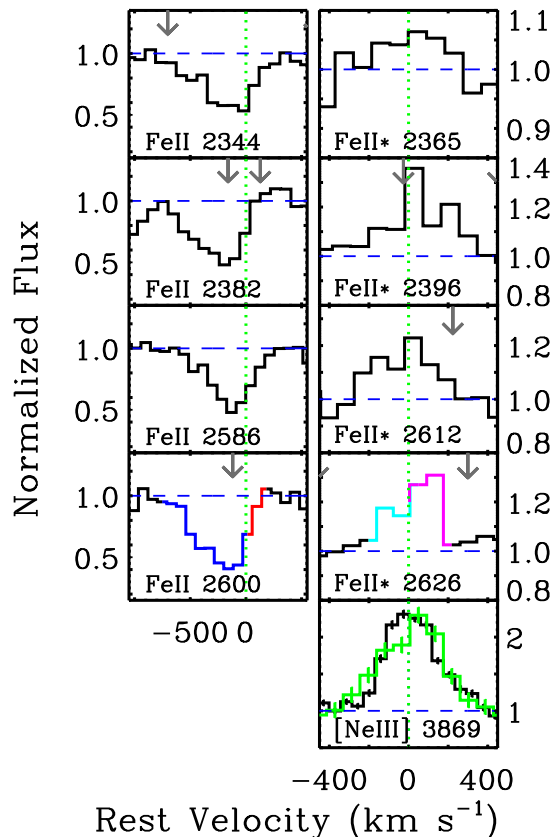


FIG. 2.— Fe II transitions in the galaxy spectrum. The systemic velocity is marked with vertical dotted lines, and the horizontal dashed line marks the continuum level. The left-hand column shows resonance absorption lines, while the right-hand column shows Fe II* emission profiles (top four panels) and the [Ne III] $\lambda 3869$ line (bottom panel; black). The green line in the bottom panel shows the coadd of the detected (and unblended) Fe II* emission lines. Gray arrows mark Fe II* transitions arising from states that cannot be radiatively excited directly from the ground state (see §4 and Table 1). We propose that the red and blue sections of the spectrum in the left-hand panel and the magenta and cyan sections in the right-hand panel arise from different areas of the outflow, as indicated in Figure 4.

Mg II absorption and emission are also evident in the two-dimensional spectrum of the target (Figure 3). To explore the spatial extent of the Mg II emission, we subtract a model of the two-dimensional continuum profile from the original two-dimensional spectrum. The residual emission extends up to $\sim 2''$ from the spatial center of the galaxy continuum, and extends well beyond the stellar structure (i.e., the components of the galaxy which generate the continuum flux near Mg II). The flux of the two emission features at 2796 \AA below and above the galaxy continuum are (8.0 ± 0.4) and $(4.4 \pm 0.4) \times 10^{-18} \text{ ergs cm}^{-2} \text{ s}^{-1}$, respectively, and have flux-weighted velocity centroids of $\sim 26 \text{ km s}^{-1}$ and 74 km s^{-1} . The corresponding fluxes at 2803 \AA are (4.0 ± 0.3) and $(2.5 \pm 0.4) \times 10^{-18} \text{ ergs cm}^{-2} \text{ s}^{-1}$. There is a significant difference in the flux of the 2796 \AA line in these two locations; this may reflect the geometrical distribution of the emitting gas, suggesting a lack of spherical symmetry. Combined, these features contribute most ($\sim 80\%$) of the total 2796 \AA flux. In Figure 3c, we also

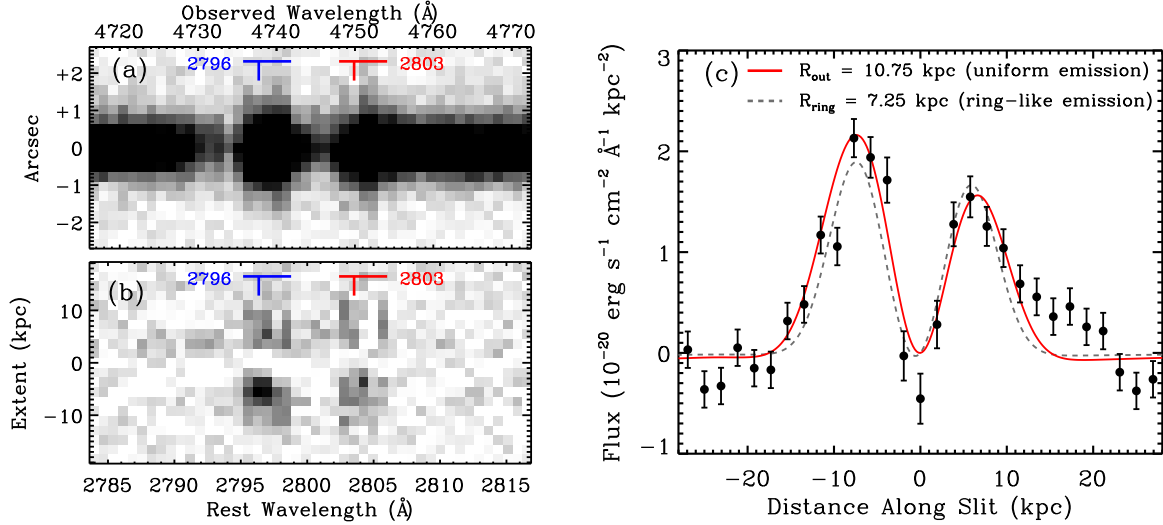


FIG. 3.— (a): Two-dimensional Keck/LRIS spectrum of the Mg II doublet, evident in emission and absorption. The vertical blue and red lines mark the systemic velocities of the Mg II doublet transitions. (b): A model of the galaxy continuum, scaled by the flux in the spatial center of the object, has been subtracted from the spectrum shown in panel (a). The residual flux at $\lambda = 2796$ Å and $\lambda = 2803$ Å indicates that the Mg II emission is broader than the continuum, and extends on both sides to $\sim 1''$ ($\gtrsim 7$ kpc). (c): The spatial profile of the spectrum shown in panel (b), averaged over the full velocity extent of both emission lines (black circles). The lines show the continuum-subtracted emission profile from models with different distributions of line-emitting material. See Section 3.1 for details.

present the continuum-subtracted spatial profile averaged over the velocity range covered by *both* lines. Errors calculated from the extraction of continuum-subtracted spatial profiles at other locations along the slit are consistent with the error bars in the Figure in the wings of the profile and are larger by up to a factor of ~ 2 near the profile center. Spatially extended emission from strong lines arising in H II regions, e.g., H γ and [O II], is not detected.

Finally, we develop a rudimentary model for the spatial distribution of the line-emitting material to constrain its distance from the galaxy’s center. Because Mg II is emitted in star-forming recombination regions (Kinney et al. 1993), the model assumes that the emission is distributed over both the galactic H II regions and a more extended area with variable geometry and size. The nebular emission component is distributed in roughly the same way as the young stars in the galaxy; i.e., as in the HST/ACS b_{435} -band image. We create a “continuum” model by scaling this image such that when it is convolved with a two-dimensional Gaussian to simulate the effects of seeing and is “observed” with the correct slit orientation, the spatial distribution of the flux passing through the slit matches the galaxy continuum profile. We then assume that the extended emission is distributed either (1) with uniform surface brightness and an outer radius R_{out} , or (2) in a ring with radius R_{ring} and thickness ~ 1 kpc.

We generate several realizations of these models by allowing the ratio of the total luminosity from the extended emission to the luminosity in the section of the galaxy centered on the slit (f_{gal}) to vary between 0.5 and 3 in increments of 0.25, and by varying either R_{out} or R_{ring} between 5 and 13 kpc in increments of 0.25 kpc. These realizations are added to the b_{435} image, and the resulting “extended emission image” is convolved with

a Gaussian and “observed” through the slit. We then subtract the profile of the continuum model from the extended emission model profile, first scaling the continuum profile to the peak flux value in the extended emission profile. In general, we find that the uniform surface brightness model provides acceptable fits to the data if $1.25 < f_{\text{gal}} < 2.5$, although adjustments in the value of R_{out} are required. With $f_{\text{gal}} = 1.5$, R_{out} must exceed 9.5 kpc to match the observations. As f_{gal} increases, values in the range $8.25 \text{ kpc} < R_{\text{out}} < 13 \text{ kpc}$ provide an excellent match to the observed emission (Figure 3c; red solid line). Additionally, though the best-fit uniform surface brightness model yields a lower χ^2 value than any of the ring-like emission models, realizations of the latter with $6.5 \text{ kpc} \leq R_{\text{ring}} < 8.25 \text{ kpc}$ and $f_{\text{gal}} \sim 1.25$ are allowed by the data (gray dashed line). While this framework is quite simplistic, the models suggest that the material giving rise to the Mg II emission is distributed over a large area, extending to distances of at least 6.5 kpc.

3.2. Characteristics of Fe II* Emission

The Fe II ion is notable for its multitude of permitted transitions in the wavelength range 2000 - 3000 Å (Table 1). We observe several Fe II resonance lines in absorption (Figure 2) which are blueshifted by $\sim -200 \text{ km s}^{-1}$, similar to Mg II. We also identify several transitions in emission (Figure 2). All of these are consistent with transitions arising exclusively from the $J = 9/2$ or $7/2$ upper levels (see Table 1 for details).

The velocity limits of each emission line, v_{cen} , and v_{peak} are determined as for Mg II. Both v_{peak} and v_{cen} are redward or within 30 km s^{-1} of systemic in 4 of 5 detected lines. In an inverse variance-weighted stack of the emission lines at 2365 Å, 2396.35 Å, 2612 Å, and 2626 Å (overplotted in green in Figure 2), $v_{\text{peak}} = +50 \text{ km s}^{-1}$

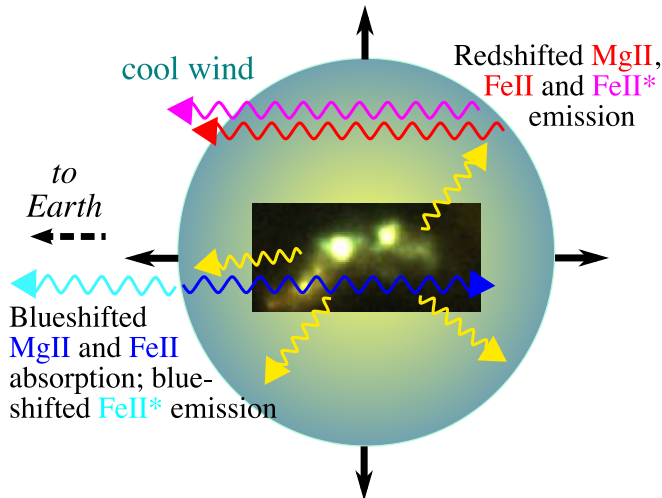


FIG. 4.— Cartoon illustrating resonant scattering in Mg II and fluorescence in Fe II. The galaxy is surrounded by an expanding, spherically symmetric wind. Mg II and Fe II ions in the section of the wind closest to Earth absorb continuum photons at the rest frequency of the ions; this produces a blueshifted absorption line profile (shown in blue in Figures 1 and 2). Ions in the back side of the wind scatter photons with wavelengths redshifted relative to systemic velocity; these photons travel through the wind and into our line of sight (shown in red in Figures 1 and 2). Because there are several energy levels accessible to Fe II, the photons are not resonantly trapped, and escape from the wind via emission to excited states (indicated in cyan and magenta in Figure 2).

and $v_{cen} = +8 \text{ km s}^{-1}$. We note that this differs from the velocity profiles of nebular emission lines such as [Ne III], $\text{H}\delta$, and $\text{H}\gamma$, which have peak velocities near or blueward of systemic and blueward of v_{cen} . The [Ne III] velocity profile is shown in Figure 2 as a reference; this line is chosen because the profile is not contaminated by broad stellar absorption. The velocity profiles of the Fe II* emission lines significantly differ both from those of the Fe II resonance absorption lines and from the profiles of lines tracing the kinematics of the galactic H II regions.

4. DISCUSSION

We now suggest a possible production mechanism for the observed Mg II and Fe II* emission: photon scattering in a large-scale galactic outflow. As discussed in Section 1, this has been invoked in previous work to explain the P Cygni profile of $\text{Ly}\alpha$ emission in LBGs. Similarly to $\text{Ly}\alpha$, Mg II is likely to have high optical depths in the ISM of star-forming galaxies. Additionally, the Mg II transitions of interest arise from a set of two close upper energy levels that can only decay to the ground level. Mg II photons are therefore resonantly trapped in high optical depth conditions (see also Prochaska et al., in prep.).

Figure 4 illustrates the effects of a transition resonantly trapped in an outflow. Mg II ions in the section of the wind closest to Earth absorb continuum photons at the Mg II transition in the rest frame of the gas; this produces a blueshifted absorption line profile. Mg II ions in the far section of the wind scatter photons with wavelengths redshifted relative to the rest frame of the front part of the wind; these photons can therefore travel through the wind, generating emission at and redward of the systemic velocity. Such an outflow may also produce

the spatially extended emission evident in Figure 3. This emission arises from gas above and below the galaxy in Figure 4 moving tangentially to our line of sight, and so is expected to occur near the systemic velocity.

A similar mechanism can produce the observed Fe II* emission. Ions in the front side of the wind will again produce blueshifted absorption in resonance transitions, as in the case of Mg II. The excited ions in *all parts* of the wind will then emit photons and decay to states with $|\Delta J| \leq 1$, including Fe II* transitions to fine-structure levels with $J \geq 5/2$. We note that these are the only transitions observed; i.e., we do not detect emission lines with lower energy levels having $J = 3/2$ or $1/2$, and the detection of these lines in higher-S/N data would rule out this picture. Further, the observed emission arises from the same upper levels excited in the resonance transitions. The lack of observed absorption from these excited states indicates that they decay before the ion is re-excited. The wind is therefore completely optically thin to the observed Fe II* photons.

5. IMPLICATIONS

The mechanism described above is only one of several which may produce Mg II and Fe II* emission. These lines may be produced in recombination regions (Kinney et al. 1993) or in AGN (Vestergaard & Wilkes 2001). However, because the kinematics of all the lines discussed are qualitatively different from the kinematics of the nebular emission in the spectrum, and because our analysis of the spatial distribution of the Mg II emission suggests that it arises from distances out to at least $\sim 7 \text{ kpc}$ from the galaxy center, we consider photon scattering the most probable production mechanism for the observed emission. As such, *our observation represents the first detection of a galactic outflow in emission in a distant galaxy, and provides the first constraints on the minimum spatial extent ($\gtrsim 7 \text{ kpc}$) and morphology of this outflow*. Stringent constraints on the mass and energetics of the gas require a solution to the radiative transfer equation in the wind. However, here we use our EW measurements (Table 1) to make a crude estimate of the physical properties of the outflow. The ratio of the Mg II absorption line EWs (i.e., the “doublet ratio”) is ~ 1.64 ; this indicates that the optical depth is $\tau_{2796} \gtrsim 1.4$ along the line of sight to the galaxy itself (Spitzer 1968; Jenkins 1986; Rubin et al. 2010b). This analysis does not account for the effects of the emission on the absorption EWs; however, because the 2803 \AA absorption line is filled in by emission from both transitions, the EW is likely reduced more than the 2796 \AA absorption EW. We therefore consider this estimate a conservative lower limit. Assuming a covering fraction equal to 1 and invoking Eq. 2-41 of Spitzer (1968), $\tau_{2796} \gtrsim 1.4$ implies a column density of $N_{\text{MgII}} > 10^{14} \text{ cm}^{-2}$.

In the case of an isotropic wind which is fully covered by the slit, the sum of the EWs of absorption and emission in a given transition equals zero (Prochaska et al., in prep.). The sum of the Mg II EWs measured in the galaxy spectrum is $\sim 0.7 \text{ \AA}$, indicating that the outflow is nearly isotropic, and hence that the sections of the wind observed in emission have $\tau_{2796} \gtrsim 1.4$ (i.e., similar to the portions of the wind observed along the line of sight). With $v_{\text{wind}} = 300 \text{ km s}^{-1}$, $\Delta v_{\text{wind}} =$

500 km s⁻¹, and $\Delta R_{\text{wind}} = 7$ kpc, and using the equation $\tau_{2796} = (\pi e^2 / m_e c) f_{2796} \lambda_{2796} n_{\text{MgII}} (\Delta R_{\text{wind}} / \Delta v_{\text{wind}})$, modified from Eq. 8.45 of Lamers & Cassinelli (1999), we find a number density $n_{\text{MgII}} \sim 7 \times 10^{-9}$ cm⁻³. Neglecting any ionization correction, and assuming solar abundance ($\log \text{Mg}/\text{H} = -4.42$) and a factor of -1.2 dex dust depletion (Savage & Sembach 1996), the corresponding limit on n_{H} is 0.003 cm⁻³. While this estimate suffers from large uncertainties, the limits on both the wind radius and n_{H} determined from this analysis provide novel information which is crucial to constraining both the mass and energy carried by the outflow.

Beyond the analysis presented here, future studies of these emission features in other galaxies will provide critical insight into the impact of galactic winds on the redistribution metals and dust to the outer halos of galaxies (Ménard et al. 2010) and the IGM (Simcoe et al. 2002). A rest-frame UV spectroscopic survey of $0.3 < z < 1.4$ galaxies (Rubin et al. 2010, in prep.) reveals that these emission features are quite common at $z \sim 1$, and thus

may be targeted for follow-up observations with IFUs to create maps of the outflow morphology. High spectral resolution observations of Fe II* emission will probe the gas kinematics in detail from the outskirts of the wind to deep within the galaxy, both on the far and near side of the stellar disk; in addition, the observed flux in the fine structure lines can provide an independent constraint on the radial extent of the gas (e.g., Prochaska et al. 2006). These studies, when performed in concert with radiative transfer modeling of the emission features, will probe the morphology of outflows at an unprecedented level of detail in numerous distant galaxies.

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TABLE 1
OBSERVED TRANSITIONS AND LIMITS

	E_{high} cm^{-1}	E_{low} cm^{-1}	J	λ \AA	A s^{-1}	W_r \AA	Flux ^a $10^{-17} \text{ ergs cm}^{-2} \text{ s}^{-1}$	v_{peak} km s^{-1}	v_{cen} km s^{-1}	v_{extent} km s^{-1}
Fe II UV1	38458.98	0.00	9/2 \leftarrow 9/2	2600.17	Absorption	2.54 ± 0.08	...	...	...	...
	38458.98	384.79	9/2 \rightarrow 7/2	2626.45	3.41E+07	-0.85 ± 0.08	0.959 ± 0.082	50	-28	-288 \rightarrow 218
	38660.04	0.00	7/2 \leftarrow 9/2	2586.65	Absorption	1.89 ± 0.07	...	...	...	...
	38660.04	384.79	7/2 \rightarrow 7/2	2612.65	1.23E+08	-0.57 ± 0.07	0.756 ± 0.092	-62	-20	-317 \rightarrow 277
	38660.04	667.68	7/2 \rightarrow 5/2	2632.11	6.21E+07	-0.20 ± 0.05	0.266 ± 0.064	162	162	-6 \rightarrow 331
	38858.96	667.68	5/2 \rightarrow 5/2	2618.40	4.91E+07	...	< 0.236	...	...	...
	38858.96	862.62	5/2 \rightarrow 3/2	2631.83	8.39E+07	...	b	...	...	...
	39013.21	667.68	3/2 \rightarrow 5/2	2607.87	1.74E+08	...	< 0.271	...	...	...
	39013.21	862.61	3/2 \rightarrow 3/2	2621.19	3.81E+06	...	< 0.251	...	...	...
	39013.21	977.05	3/2 \rightarrow 1/2	2629.08	8.35E+07	...	< 0.231	...	...	...
	39109.31	862.61	1/2 \rightarrow 3/2	2614.60	2.11E+08	...	< 0.267	...	...	...
	39109.31	977.05	1/2 \rightarrow 1/2	2622.45	5.43E+07	...	< 0.239	...	...	...
Fe II UV2	41968.05	0.00	11/2 \leftarrow 9/2	2382.76	Absorption	2.00 ± 0.07	...	...	...	...
	42114.82	0.00	9/2 \leftarrow 9/2	2374.46	Absorption	1.37 ± 0.08	...	...	...	...
	42114.82	384.79	9/2 \rightarrow 7/2	2396.36	2.67E+08	-0.81 ± 0.08	1.183 ± 0.120	119	-14	-430 \rightarrow 393
	42237.03	0.00	7/2 \rightarrow 9/2	2367.59	3.21E+04	...	< 0.279	...	...	...
	42237.03	384.79	7/2 \rightarrow 7/2	2389.36	9.64E+07	...	< 0.301	...	...	...
	42334.82	667.68	5/2 \rightarrow 5/2	2399.97	1.37E+08	...	< 0.304	...	...	...
Fe II UV3	42401.30	667.68	3/2 \rightarrow 5/2	2396.15	2.67E+07	...	b	...	...	...
	42658.22	0.00	7/2 \leftarrow 9/2	2344.21	Absorption	2.08 ± 0.08	...	...	...	...
	42658.22	384.79	7/2 \rightarrow 7/2	2365.55	5.90E+07	-0.17 ± 0.06	0.252 ± 0.091	45	0	-232 \rightarrow 230
	43238.59	384.79	5/2 \rightarrow 7/2	2333.52	1.27E+08	...	< 0.301	...	...	...
	43238.59	667.68	5/2 \rightarrow 5/2	2349.02	1.09E+08	...	< 0.292	...	...	...
	43238.59	862.62	5/2 \rightarrow 3/2	2359.83	5.42E+07	...	< 0.284	...	...	...
Mg II	43620.96	862.61	3/2 \rightarrow 3/2	2338.73	1.09E+08	...	< 0.277	...	...	...
	...	...	...	2796.35	Absorption	2.65 ± 0.07	...	...	...	...
	...	...	...	...	...	-1.69 ± 0.05	1.907 ± 0.065	60	89	-99 \rightarrow 297
	...	...	...	2803.53	Absorption	1.62 ± 0.05	...	...	...	...
[Ne V]	...	...	...	...	...	-1.84 ± 0.06	2.086 ± 0.079	161	225	-76 \rightarrow 556

[O II]	...	...	...	3426.98	...	-0.61 ± 0.13	0.466 ± 0.103	51	212	-271 \rightarrow 695
[Ne III]	...	...	...	3727.10	...	-66.74 ± 0.25	50.263 ± 0.190	194	132	-464 \rightarrow 732
H δ	...	...	...	3869.84	...	-5.74 ± 0.13	4.673 ± 0.111	-26	25	-373 \rightarrow 436
H γ	...	...	...	4102.90	...	-4.84 ± 0.15	3.591 ± 0.117	-39	38	-312 \rightarrow 397
H γ	...	...	...	4341.69	...	-14.42 ± 0.30	7.912 ± 0.207	4	81	-407 \rightarrow 621

NOTE. — Rest-frame EW, flux and kinematic measurements from LRIS spectroscopy. Upper and lower energy levels, orbital angular momenta (J) and Einstein coefficients are given for Fe II transitions (Morton 2003). Errors are 1σ uncertainties with 3σ limits. Blended transitions are marked with “b”. We check Fe II identifications by comparing A coefficients among different transitions. For optically thin gas, the flux ratio of two lines that originate from the same excited state is approximately the ratio of the corresponding A coefficients. E.g., the flux ratio of the 2612 Å and 2632.11 Å transitions ($E_{\text{high}} = 38660.04 \text{ cm}^{-1}$) is $\sim 2.8 \pm 0.7$, i.e. $\sim 1.2\sigma$ higher than the ratio of A coefficients (1.98).

^a Line fluxes are determined by summing the continuum-subtracted spectrum over the velocity range of the line, as described in §3.1.